

## ASSESSMENT OF TRANSURANICS STABILIZATION IN PWRs

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### ABSTRACT

The stabilization of transuranics (TRU) in a PWR fuel cycle was evaluated for the CORAIL assembly. Alternative assembly designs (a *highly moderated and modified CORAIL-TRU assembly* and a *homogeneous Thorium-TRU assembly*) were also investigated to assess the potential of obtaining a near-zero TRU mass balance (i.e., the net TRU production per assembly) and low power peaking factor. The radiotoxicity of the nuclear waste sent to the repository environment and the impact of TRU stabilization on the future TRU stockpile were also evaluated. Assembly level mass flow analyses have shown that TRU mass balances in the range of 0.2 to 1.4 kg/assembly are achievable within 7 recycles of the TRU, compared with 6.5 kg/assembly for a reference UO<sub>2</sub> assembly. The study also revealed that the radiotoxicity of the repository waste generated by these TRU-containing assemblies at 10 years after disposal is roughly half that of a reference UO<sub>2</sub> assembly; furthermore, the radiotoxicity falls below that of natural uranium ore after about 500 years because only a small fraction of the TRU (0.1%) is passed to the waste repository. Finally, the future TRU stockpile could be reduced by implementation of TRU multi-recycling in the CORAIL or alternative assemblies in a current-generation PWR core.

### 1. INTRODUCTION

The stabilization of transuranics (TRU) in a PWR fuel cycle would provide the benefit of reducing the radiotoxicity of waste sent to a repository environment and could make nuclear power a viable option in the future mix of energy production in the U.S. By stabilization, it is implied that there is no net production of TRU in each fuel assembly during irradiation in a reactor. Thus, the amount of TRU passed to the repository is limited to that lost in fuel separation between irradiation cycles. The possibility of completely utilizing the TRU in a PWR fuel cycle is quite attractive, as this might prove more economical than introducing additional fuel cycles or systems (for example accelerator-driven systems) purposefully for TRU transmutation.

The possibility of using the CORAIL assembly concept for the stabilization of plutonium in the LWR fuel cycle was first proposed by the French CEA [1]. In the CORAIL concept, a heterogeneous fuel assembly is used in existing LWR core designs without adversely affecting core safety and operational parameters and fuel cycle infrastructures. Since it was found that the CORAIL concept is

capable of stabilizing the plutonium inventory, the feasibility of stabilizing the TRU in the nuclear fuel cycle (called CORAIL-TRU hereafter) was investigated.

The CORAIL-TRU assembly was first evaluated by loading (U,TRU)O<sub>2</sub> in the MOX pins of the standard design of the CORAIL assembly. However, the resulting mass balance was unsatisfactory and the power peaking factor in the assembly was rather high. Therefore, two alternative designs were investigated. In this paper, the performance characteristics of the CORAIL-TRU assembly and alternative designs for TRU stabilization are described. Specifically, the neutronics properties, radiation hazard, and the projected TRU stockpile are discussed.

## 2. CORAIL CONCEPT

In the CORAIL concept, a full-core loading of the CORAIL assemblies is assumed. The CORAIL assembly employs a standard 17x17 PWR fuel assembly containing 180 UO<sub>2</sub> pins in the interior and 84 MOX pins in the peripheral region (see Figure 2.1). In order to reduce the power peaking factor and maintain reactivity coefficients similar to those in a typical UO<sub>2</sub> fuel assembly, the MOX fuel rods are positioned in the peripheral region of an assembly and the fraction of MOX pins in the assembly is limited to roughly one third of all fuel pin locations.

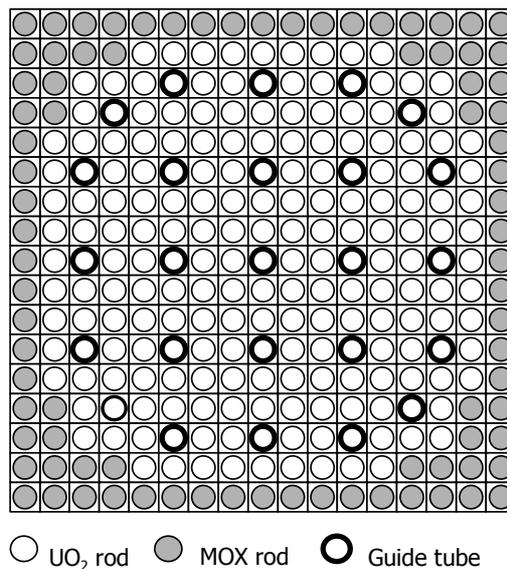


Figure 2.1. Pin Loading Pattern of CORAIL Assembly

Figure 2.2 presents a flow diagram for the TRU multi-recycling methodology utilized in the CORAIL concept. For a given cycle, the MOX pins in the assembly are fabricated from TRU extracted from the discharge of the previous cycle; the fabrication of the UO<sub>2</sub> pins requires an external source of enriched uranium. A lead-time of two years is assumed from fuel separation/assembly fabrication to its loading into the reactor. After the assembly is discharged from the reactor, a five-year post-irradiation cooling time is allowed before separation of the discharged fuel. During the separation, most of the TRU (99.9%) are recycled, while all fission products and 0.1% of the TRU are passed to the repository. Also, it is assumed that discharged uranium will either be used as a make up feed or be passed to low-level storage instead of the repository.

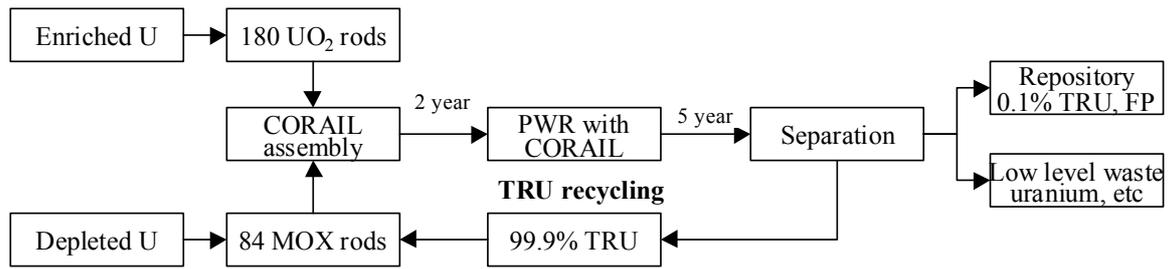


Figure 2.2. Flow Diagram for TRU Multi-recycling.

As the TRU isotopic vector changes with each cycle, the uranium enrichment in the CORAIL-TRU assembly must be determined at the fabrication step, subject to three constraints which were imposed in this study. The first constraint is on cycle length, which is met by requiring  $k_{\infty}=1.030$  at the end of cycle. Two other constraints are placed on the uranium enrichment and the power peaking factor, which are limited to 5.0% and 1.20, respectively (these last two constraints were loosened slightly for the convenience of assembly design).

### 3. COMPUTATION METHODOLOGIES

Although significant spatial dependencies are present in a PWR core, 2-dimensional, assembly-level calculations are adequate for the present scoping study of the heavy metal mass flows which result from TRU multi-recycling in a CORAIL fueled core. For this reason, we have confined the evaluations to unit assembly studies with the WIMS8 code [2]. In the WIMS8 calculations, a 172-group neutron cross section library based on JEF2.2 is available to properly account for the self-shielding effect of the higher actinide isotopes. The code is also capable of estimating the time-dependent heavy metal composition from Th-232 to Cm-245. As a benchmark exercise, the power distribution in the CORAIL assembly predicted by WIMS8 was compared with the results of an MCNP4C [3] calculation. Although the heterogeneous fuel pin configuration of the CORAIL assembly causes sharp flux gradients within the assembly, good agreement between WIMS8 and MCNP4C was obtained, indicating that WIMS8 is well-suited for predicting the pin power distribution in the CORAIL assembly.

For a core loaded with uniform assemblies in a multi-batch fuel management scheme, the fuel cycle analysis can be modeled with the linear reactivity model [5]. In this study, a 3-batch core with a cycle length of 15,000 MWd/t was assumed. According to the linear reactivity model, the critical burnup (the average burnup at the end of cycle) and the average discharge burnup are 30,000 MWd/t and 45,000 MWd/t, respectively. In order to represent the whole core state adequately with an assembly level calculation, the effect of neutron leakage through the core boundary must be accounted for in the assembly  $k_{\infty}$  value. In this work, a core leakage of 3%  $\Delta k$  was assumed. Thus, setting the uranium enrichment in the CORAIL assembly such that  $k_{\infty} = 1.030$  at the critical burnup will provide a charged assembly loading which meets the desired cycle length for the operating core.

As the TRU is multi-recycled in the CORAIL assembly, there will be a gradual buildup of higher-mass actinides in the discharged fuel, causing an increase in the radioactive properties of the discharged nuclear fuel. These must be evaluated accurately, since higher heat and radiotoxicity of the discharged fuel can have a negative impact on the reprocessing efficiencies as well as the repository environment. In order to obtain more accurate predictions of the radioactive properties of all nuclides

in the discharged fuel, a procedure to couple the results of ORIGEN2 [4] and WIMS8 was developed. To begin, both codes are utilized to predict the isotope masses in 1 metric ton of fuel depleted to the discharge burnup. The isotopic concentration predicted by ORIGEN2 is replaced by the result of the WIMS8 calculation if the isotope exists in WIMS8 depletion chain. The other concentrations are then re-normalized to conserve the total masses of the heavy metals and fission products predicted by ORIGEN2. The updated and re-normalized concentrations of all nuclides in the lattice at discharge are input to a subsequent ORIGEN2 calculation in order to predict the radioactive properties at discharge and several time points thereafter.

#### 4. MULTI-RECYCLING OF CORAIL-TRU ASSEMBLY

The attractiveness of the CORAIL concept for plutonium stabilization has motivated our interest in exploring its feasibility for TRU stabilization in current and advanced PWRs. First, the mass flow and neutronic properties were evaluated by loading (U, TRU)O<sub>2</sub> in the MOX pins of the standard design of the CORAIL assembly. The results after 7 recyclings are provided in Table 4.1, which also includes those for a typical UO<sub>2</sub> assembly as a reference.

Table 4.1. Multi-recycling in CORAIL-TRU Assembly

			7 <sup>th</sup> cycle		Reference UO <sub>2</sub>
			ANL	CEA <sup>a)</sup>	
Uranium enrichment, %			5.04	5.02	4.0
TRU content in MOX, %			12.74	12.38	-
Power peaking factor			1.202	1.20	1.06
Fissile in TRU at charge, %			38.92	38.80	4.0
Mass Balance (kg/assembly)	Pu	Charge	18.0	17.3	0.0
		Discharge	19.5	18.7	6.0
		Net	1.5	1.4	6.0
	MA	Charge	3.7	3.7	0.0
		Discharge	3.6	3.7	0.5
		Net	-0.1	0.0	0.5
	TRU	Charge	21.7	21.0	0.0
		Discharge	23.1	22.4	6.5
		Net	1.4	1.4	6.5
Reactivity coefficients <sup>b)</sup>	Boron worth (pcm/ppm)	Charge	-4.9	-4.8	-6.7
		Discharge	-2.7	-5.3	-9.4
	FTC (pcm/K)	Charge	-2.4	-2.7	-2.2
		Discharge	-4.3	-2.9	-3.6
	MTC (pcm/K)	Charge	-18	-27	-3
		Discharge	-45	-64	-72

a) Results provided by CEA [6].

b) ANL calculations of the soluble boron worth and fuel temperature coefficient (FTC) are at 0 GWd/t or 45 GWd/t with 0 ppm; moderator temperature coefficient (MTC) is at 0 GWd/t with 1631 ppm (CORAIL) or 1400 ppm (UO<sub>2</sub>) and at 45 GWd/t with 0 ppm. The CEA results are at BOC and EOC conditions.

The results of ANL calculations agree quite well with those provided by CEA [6]. The required TRU content and the TRU mass balance per assembly (mass difference between the discharge and charge) at cycle 7 are 12.74% and 1.4 kg, respectively, compared to 12.38% and 1.4 kg in the CEA results. The limitation on the power peaking factor was satisfied for the first few cycles in the ANL

calculations, but it was violated after 5 recyclings. The reactivity coefficients of the CORAIL-TRU assembly are similar to those of the reference UO<sub>2</sub> assembly design.

## 5. ALTERNATIVE ASSEMBLY DESIGNS FOR TRU STABILIZATION

### 5.1. HIGHLY MODERATED AND MODIFIED CORAIL ASSEMBLY

As shown in the previous section, the CORAIL-TRU assembly still has a sizeable TRU mass balance (1.4 kg per assembly) after 7 recyclings. Also, the relatively high power peaking factor compared with the UO<sub>2</sub> assembly is a source of concern. Therefore, redesigns of the CORAIL assembly were considered to achieve the goal of TRU stabilization in PWRs.

First, a *highly moderated and modified CORAIL assembly* was proposed by combining the features of high moderation and a modified fuel pin configuration (see Figure 5.1). Because the conversion rate of U-238 to Pu-239 decreases as the neutron spectrum becomes softer, the positive TRU mass balance in the CORAIL-TRU assembly could be reduced by increasing the moderation ratio (in this study, the moderator to fuel volume ratio was increased from 2.03 to 2.47 by reducing the fuel pin radius). Also, the power peaking factor was reduced by loading the MOX fuel pins (88) near the guide tubes, rather than on the assembly periphery. The modified fuel configuration results in a flat thermal flux distribution in the assembly; the thermal flux near the guide tubes is depressed due to the high absorption cross sections of TRU isotopes. However, since the power in the MOX pins will increase due to the high thermal fission cross-section of TRU isotopes, higher-enriched UO<sub>2</sub> fuel pins are necessary in order to obtain a flat power distribution in the modified CORAIL assembly.

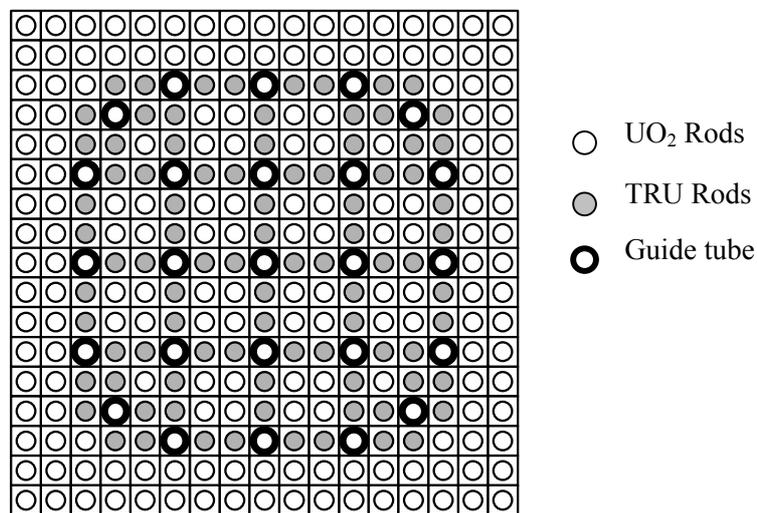


Figure 5.1. Highly Moderated and Modified CORAIL Assembly.

The results after 7 recyclings in the highly moderated and modified CORAIL assembly are summarized in Table 5.1. As expected, the power peaking factor and the TRU mass balance are improved in the highly moderated and modified CORAIL-TRU assembly: the power peaking factor and TRU mass balance per assembly are 1.150 and 0.4 kg, respectively, compared with 1.202 and 1.4

kg for the CORAIL-TRU assembly. Also, there are no significant differences in the reactivity coefficients compared with the reference UO<sub>2</sub> assembly.

Table 5.1. Comparison of Multi-recycling in CORAIL-TRU and Alternative Assemblies.

			7 <sup>th</sup> cycle			Reference UO <sub>2</sub>
			Highly moderated & modified CORAIL	Homogeneous Thorium-TRU	CORAIL-TRU	
Uranium enrichment, %			5.07	4.08	5.04	4.0
TRU/Thorium content, %			8.16/0.0	3.23/2.43	12.74/0.0	0.0/0.0
Power peaking factor			1.150	1.087	1.202	1.06
Fissile in TRU at charge, %			36.96	40.76	38.92	
Mass Balance (kg per assembly)	Pu	Charge	10.0	13.5	18.0	0.0
		Discharge	10.3	14.1	19.5	6.0
		Net	0.3	0.6	1.5	6.0
	MA	Charge	2.8	3.3	3.7	0.0
		Discharge	2.9	3.3	3.6	0.5
		Net	0.1	0.0	-0.1	0.5
	TRU	Charge	12.8	16.8	21.7	0.0
		Discharge	13.2	17.4	23.1	6.5
		Net	0.4	0.6	1.4	6.5
Reactivity coefficients <sup>a)</sup>	Boron worth (pcm/ppm)	Charge	-5.7	-4.1	-4.9	-6.7
		Discharge	-8.1	-4.9	-2.7	-9.4
	FTC (pcm/K)	Charge	-2.4	-3.2	-2.4	-2.2
		Discharge	-3.3	-3.6	-4.3	-3.6
	MTC (pcm/K)	Charge	-20	-40	-18	-3
		Discharge	-77	-81	-45	-72

a) ANL calculations of the soluble boron worth and fuel temperature coefficient (FTC) are at 0 GWd/t or 45 GWd/t with 0 ppm; moderator temperature coefficient (MTC) is at 0 GWd/t with 1631 ppm (CORAIL) or 1400 ppm (UO<sub>2</sub>) and at 45 GWd/t with 0 ppm. The CEA results are at BOC and EOC conditions.

## 5.2. HOMOGENEOUS THORIUM-TRU ASSEMBLY

By reducing the fuel pin radius, the highly moderated assembly may have thermal-hydraulic problems. Since the heat flux is inversely proportional to the fuel pin radius, the power of the highly moderated assembly must be reduced in order to obtain the same critical heat flux ratio (CHFR) as the CORAIL assembly design proposed by CEA. Furthermore, the power peaking factor (1.15 at 7<sup>th</sup> cycle) is still well above that for a typical UO<sub>2</sub> assembly (1.06).

Due to these potential problems associated with the heterogeneous assembly design, a homogeneous assembly concept was investigated. The primary idea of the homogeneous assembly concept is to load a mixture of the uranium-, thorium-, and TRU-oxide in all fuel pins (called homogeneous Thorium-TRU assembly hereafter). The power peaking factor of the homogeneous Thorium-TRU assembly is expected to be similar to that of a typical homogeneous UO<sub>2</sub> assembly. Also, the conversion of U-238 to Pu-239 would be reduced (which would reduce the net production of TRU) and replaced by the conversion of Th-232 to U-233. The thorium to uranium weight ratio should be selected so that the uranium fissile content in the discharged MOX pins is not weapons-grade.

Table 5.1 also provides the results for the homogeneous Thorium-TRU assembly after 7 recyclings. The uranium enrichment and TRU content required to meet the 15,000MWd/t cycle length are 4.08% and 3.23%, respectively. The net TRU mass balance in this homogeneous assembly is 0.6 kg and the

required thorium content is 2.43%. The power peaking factor of the homogeneous Thorium-TRU assembly is 1.09, similar to that of the reference homogeneous UO<sub>2</sub> assembly. Lastly, the reactivity coefficients for the homogeneous thorium-TRU assembly are similar to those of the UO<sub>2</sub> assembly.

## 6. RADIOTOXICITY AND PROJECTED TRU STOCKPILE

### 6.1. RADIOTOXICITY

The radiotoxicity of the reprocessing waste from the TRU-containing assemblies after continued recycling to an equilibrium state was estimated by evaluating the cancer dose [7] and water dilution hazard [8] up to 10 million years after disposal. In the CORAIL-TRU or its alternative concepts, the waste passed to the repository is limited to 0.1% of the TRU and all fission products; most of the TRU (99.9%) are recycled and the discharged uranium will either be used as a make up feed or stored as low-level waste. On the other hand, all of the discharged heavy metal mass from the reference UO<sub>2</sub> assembly is passed to the repository because the once-through cycle concept does not reprocess the spent nuclear fuel. In all cases, a five-year cooling time was assumed before the disposal.

Figures 6.1 and 6.2 show the normalized radiotoxicity of the waste sent to the repository for a number of cases. The radiotoxicity values were normalized to that of the natural uranium ore which must be mined to produce the enriched uranium in the assembly; to produce the MOX pins, it is assumed that an ample supply of depleted uranium is available without additional mining. In these figures, HM-TRU and TMOX denote the highly moderated and modified CORAIL assembly and the homogeneous Thorium-TRU assembly, respectively. The case labeled CORAIL-Pu means the original CORAIL assembly concept for stabilizing plutonium, in which all minor actinides (MA) and fission products, as well as 0.1% of the Pu, are passed to the repository. For all cases but the reference UO<sub>2</sub> assembly, the discharged material is from the 7<sup>th</sup> cycle of a multi-recycling scheme.

Ten years after disposal, the radiotoxicity of the waste from the TRU-containing assemblies is about a factor of 2 smaller than the waste from the reference UO<sub>2</sub> assembly. At this point, the fission products dominate the hazard (about 99%), but the radiation hazard associated with the shorter-lived fission products quickly decreases. Thus, in those cases which utilize TRU recycling, the radiotoxicity falls below that of the mined natural uranium ore (normalized radiotoxicity = 1.0) after about 500 years because only a small fraction of the TRU (0.1%) is passed to the repository. The radiotoxicity of the UO<sub>2</sub> and CORAIL-Pu assemblies are still significant at 1000 years due to the disposal of plutonium and/or minor actinides.

### 6.2. PROJECTED TRU STOCKPILE WITH TRU STABILIZATION CONCEPTS

Currently, 104 commercial nuclear power plants are operating in the United States with an electrical generation capacity of 97.4 GW; the inventory of spent nuclear fuel is 38,414 tons [9]. The estimated spent nuclear fuel will be twice that of the current amount in 2020, amounting to 1002 metric tons of TRU.

In this work, the stockpile of TRU outside the nuclear power plant environment after 2020 was estimated for several scenarios with an optimistic view of the future US nuclear enterprise. In order to sustain the commercial environment without any significant changes to technology or added safety concerns, the fuel cycle concepts were restricted to UO<sub>2</sub> and CORAIL (or its alternative) assembly designs. Table 6.1 contains the calculated heavy metal mass flows for full-core loadings of different

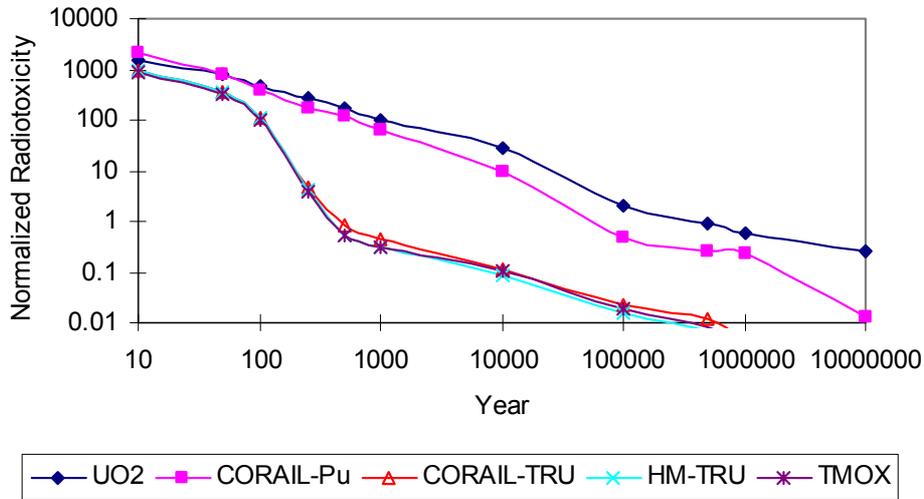


Figure 6.1. Comparison of Radiotoxicity in Terms of Cancer Dose.

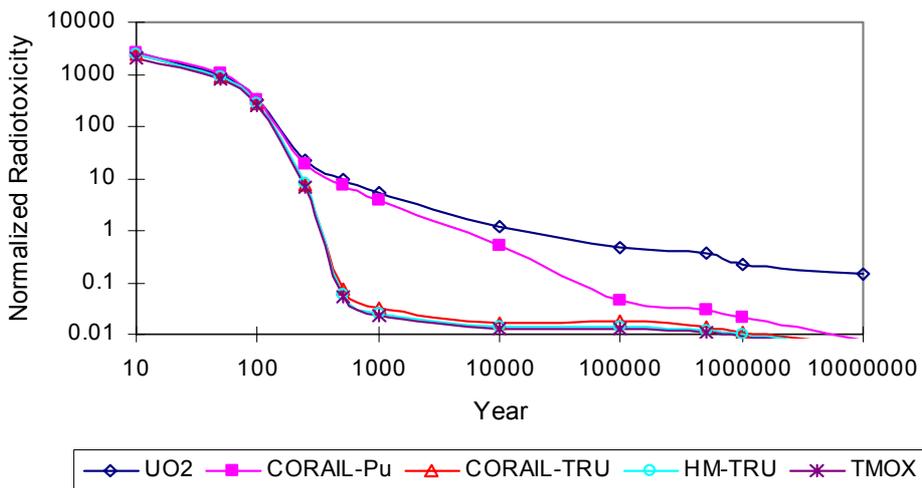


Figure 6.2. Comparison of Water Dilution Hazard.

fuel assemblies, in which HM-TRU and TMOX denote the “highly moderated and modified CORAIL assembly” and “homogeneous Thorium-TRU assembly”, respectively. In this table, the TRU mass which is sent to a dedicated transmutation system or radioactive waste repository from the CORAIL (or alternative) concepts is much smaller than the corresponding value for the UO<sub>2</sub> assembly because most of the discharged TRU (99.9%) is recycled.

Table 6.2 provides the estimated TRU stockpile in the US for five scenarios. In preparing this table, the demand for nuclear power and, consequently, the TRU production rate were assumed to grow 2.4% each year (the electricity increment estimated by the Energy Information Administration with an optimistic view of the US economy growth [9]). Scenario 1 represents the current, once-through nuclear fuel cycle. For the other scenarios, a government-owned transmutation system consisting of thermal- (Tier 1) and fast-spectrum (Tier 2) systems is assumed to be available to provide further reduction of the TRU stockpile. The number of Tier 1 ((U,TRU)O<sub>2</sub>-fueled LWR) and Tier 2 (TRU/Zr-fueled Accelerator Driven System) units assumed in the transmutation system is arbitrary,

but within realistic values. In Scenarios 3 to 5, Tier-1 was assumed to be omitted. The TRU destruction rates were taken from the AAA system studies performed in FY-2001[10].

In Scenario 1, the TRU stockpile at 2050 is about twice the amount at 2020. The TRU stockpile could be reduced by introducing a TRU transmutation system (Scenario 2), but it is still quite large (185% of the value at 2020). The relatively large TRU stockpiles in Scenarios 1 and 2 are caused by the high TRU production rates in the commercial nuclear power sector. The resulting TRU stockpiles in Scenarios 3 to 5 are much smaller because the commercial-side TRU production rate has been greatly reduced. Therefore, the reduction of the TRU production rate on the commercial-side with the CORAIL or its alternative concepts, may be a useful approach to reduce the TRU stockpile in the future.

Table 6.1. Heavy Metal Mass Flow of Different Core Concepts.

Core concept	UO <sub>2</sub>	CORAIL-Pu	HM-TRU	TMOX
Capacity (GWt) <sup>a)</sup>	300	300	300	300
Discharge burnup (GWd/t)	50	45	45	45
Capacity factor (%)	85	85	85	85
Charge (t/year)	1861.5	2068.3	2068.3	2068.3
Uranium	1861.5	2014.2	2012.2	2003.3
Pu	0.0	53.4	43.9	52.3
MA	0.0	0.8	12.3	12.8
TRU (recycling)	0.0	54.1	56.3	65.1
Discharge (t/year)	1765.8	1971.7	1971.7	1971.5
Uranium	1739.4	1909.8	1905.0	1904.1
Pu		56.4	45.2	54.6
MA		5.4	12.7	12.8
TRU	26.4	61.8	57.9	67.4
TRU to transmutation system or stockpile (t/year)	26.4	5.47	0.06	0.07

a) The capacity 300 GWt is similar to the current capacity of US.

Table 6.2. Comparison of Estimated TRU Stockpile at 2050.

Scenario	TRU production <sup>a)</sup> (t/year)	TRU Transmutation System		TRU Stockpile (ton)	
		Unit <sup>b)</sup>	TRU destruction (t/year)	at 2020	at 2050
1. Once-through cycle with UO <sub>2</sub>	26.4	-	0	1002	2169
2. UO <sub>2</sub> + TRU Transmutation	26.4	20/5	10.41		1857
3. CORAIL-Pu + TRU Transmutation	5.47	-/5	1.17		1209
4. HM-TRU + TRU Transmutation	0.06	-/5	1.17		970
5. TMOX + TRU Transmutation	0.07	-/5	1.17		970

a) TRU production rate in 2020. Rate increases by 2.4% each year thereafter.

b) Number of plants in Tier 1/Tier 2 of a government-owned transmutation system.

## 7. CONCLUSION

The CORAIL assembly and alternative concepts for TRU stabilization were evaluated in this study. It was found that after 7 cycles, the CORAIL-TRU assembly still has a positive TRU mass balance (1.4 kg per assembly) because of the high conversion of U-238 to Pu239. The power peaking factor is also relatively high (1.202, compared with 1.06 for a UO<sub>2</sub> assembly) because of large flux gradients in the assembly. In order to reduce the power peaking factor and to obtain a near zero TRU mass balance, alternative assemblies, a *highly moderated and modified CORAIL-TRU assembly* and a *homogeneous Thorium-TRU assembly*, were proposed and evaluated.

The highly moderated and modified CORAIL-TRU assembly design has 88 TRU-containing MOX fuel pins near the guide tubes and a higher moderator to fuel volume ratio (2.47, compared with 2.03 for the CORAIL design). It was observed that because of the softer neutron spectrum, the required TRU content decreases from 12.74% to 8.16% and the reactivity coefficients are closer to those for the reference UO<sub>2</sub> assembly. Additionally, the TRU is nearly stabilized in this design (0.4 kg per assembly) because the production of plutonium decreases significantly. While the power peaking factor is less than the limiting value (1.20), this assembly may result in thermal-hydraulic problems (e.g., reduction of the CHF margin) due to the smaller radii of fuel pellet and cladding.

The primary idea of the homogeneous Thorium-TRU assembly is to replace the uranium in a homogeneous UO<sub>2</sub> assembly with a mixture of uranium, thorium and TRU to reduce the conversion of U-238 to Pu-239. The results indicate that the required uranium enrichment and TRU content to meet the specified cycle length are 4.08% and 3.23%, respectively, with 2.43% thorium content. The TRU mass balance is 0.6 kg per assembly and the power peaking factor (1.09) is similar to the reference UO<sub>2</sub> assembly. The reactivity coefficients are similar to those of the other TRU assemblies evaluated in this study.

An investigation of the radiotoxicity of the reprocessing waste was also performed for the various concepts. It was found that the waste from the TRU-containing assemblies at 10 years after disposal is roughly half that of the UO<sub>2</sub> assembly waste. Furthermore, the radiotoxicity falls below that of natural uranium ore after about 500 years because only a small fraction of the TRU (0.1%) is passed to the waste repository.

An estimation of the future TRU stockpile was performed. This study indicated that the future TRU stockpile could be reduced by implementing the TRU multi-recycling concept in either the CORAIL assembly or alternative assembly designs.

In conclusion, these results indicate that from a physics perspective it is possible to multi-recycle TRU in a thermal PWR. Compared to a UO<sub>2</sub> fuel cycle, the reactor cycle length can be maintained by adjusting the MOX and uranium enrichments, and the heterogeneous assembly design conserves the reactivity coefficients. However, multiple TRU recycling leads to a significant increase in the higher actinide content of the CORAIL assembly. This will complicate fuel handling (e.g. worker dose from neutron or gamma sources) compared to standard UO<sub>2</sub> or MOX assemblies, and may be unfeasible in existing reactors. Thus, it is expected that *fuel cycle considerations* will constrain the extent of TRU recycle that can be practically achieved.

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